

Treatment Technology to Meet the
Interim Primary Drinking Water Regulations for
Inorganics: Part 5

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Cincinnati, OH

Jul 80



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The fifth in a series summarizing existing treatment
technology to meet the inorganic National Interim Primary
Drinking Water Regulations, this report describes current
methods for removing barium and radionuclides from drinking
water.

KEYWORDS: *Barium, *Potable water, *Water treatment.

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tant because all of the impurities are removed in the filter, and the retention period ahead of the filter media is short. At a filter rate of 3.4 mm/s (5 gpm/sq ft) in a filter with a water depth 2.4 m (8 ft) over the media, the water is in the filter only 12 min before reaching the media. Depending on the coagulation time, the total time ahead of the media may only be 20-30 min.

In order to produce the maximum quantity of high quality filtered water with the minimum use of wash water, several factors must be considered. For filter production the hours of operation—multiplied by filtration rate and divided by the terminal head loss across the media—give a useful parameter for evaluating the operation of a particular media design. In order to achieve the optimum efficiency for a given plant, chemical application and mixing must be adjusted appropriately to accommodate variations in the raw water quality.

Where a major water supply is made up of more than one body of water in different watersheds or where different intakes exist, it is often necessary and always advantageous to continuously monitor the turbidity of the individual supplies, so that the treatment process can be designed for optimum efficiency. It is often possible to dilute the waters of a more turbid body of water with cleaner waters from other sources of supply.

Turbidity monitoring should be carried out at several points in the plant, with the raw water and filtrate being the normal minimum. Other points would be after coagulation, at the interface between the sand and coal of the filter, and at the point where water leaves the treated water storage and enters the distribution system.

Most physical and chemical analyses of the water can be carried out on a continuous basis. Free ammonia cannot be analyzed accurately and reliably except by laboratory samples. Where raw water supplies have free ammonia levels approaching 0.2 mg/L and where retention times are too short for laboratory analysis of samples, it may be necessary to superchlorinate above the breakpoint in order to ensure that a free residual is present.

Variables to be monitored. The raw water and in-plant monitoring needed will vary with the water quality and plant design. All plants should monitor turbidity, temperature, pH, and bacterial content of the raw water. Some will monitor algae, free ammonia, iron, manganese, and color depending on the source of supply. At the filter, turbidity monitoring would be carried out on the filtrate and probably at the sand-coal interface. Monitoring the filters provides a valuable indication of the condition of each and assists in maintaining a low filtered water turbidity. The latter can be very valuable in a direct filtration plant to evaluate the effects of the chemical treatment, to provide a warning of filter breakthrough, and to analyze the floc shear strength and consequent need for polymer or other coagulant. Residual aluminum would also be monitored on the filtrate, and the alum dosing would be adjusted or substituted by other coagulants should the level increase to an unacceptable level.

Methods of plant control. The operation and control of a filtration plant fall into two areas—hydraulic control and process control. Hydraulic control, including control of pumps, filter rate, and filter backwashing, can be and has been oper-

ated automatically for many years. None of these functions is very different in a direct filtration plant, as compared to a conventional plant with sedimentation, except possibly in the duration of the wash rate applied to the filters. Filter wash can be initiated by filtrate quality, high head loss across the media, or by time. These functions can be automated using analog systems or a process controller.

Most plants today still use manually adjusted chemical feeds from monitored information with analog control loops to sustain feed rates. Alarms will indicate substantial deviations. Pilot tests of filter media can be very valuable in predicting trends and in evaluating the effectiveness of chemical application.

The trend is toward more automation, particularly with direct filtration, because a process controller will respond quickly to variations in the monitored input data. Many plants have data logging, but few have true process controllers. A true process controller requires appropriate algorithms which take time to develop.

A fully automated plant can employ analog control of the chemical feed loops with process controller supervision of the analog loop settings. The plant may have direct digital control with all variables sustained directly by the process controller. The latter sometimes has analog backup in case of computer failure.

A report approved by the T & P Council, prepared by the Direct Filtration Subcommittee of the AWWA Filtration Committee. Subcommittee members are S. Bishop, T. F. Craft, D.R. Fisher, M. Ghosh, P.W. Prendiville, K.J. Roberts, S. Steimle, and J. Thompson.

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Treatment Technology to Meet the Interim Primary Drinking Water Regulations for Inorganics: Part 5

Thomas J. Sorg and Gary S. Logsdon

The fifth in a series summarizing existing treatment technology to meet the inorganic National Interim Primary Drinking Water Regulations, this report describes current methods for removing barium and radionuclides from drinking water.

Barium Removal From Water

Health effects. Because of its toxic effect on the heart, blood vessels, and nerves, barium was placed in the USPHS

Drinking Water Standards in 1962.¹ Even prior to this action, concern for barium in drinking water existed because the 1948 USPHS Drinking Water Standards² stated that "salts of barium... shall not

be added for water treatment purposes." With almost no new health effects data available on which to base a modification to the 1962 limit, EPA maintained the maximum contaminant level (MCL) at 1.0 mg/L.³

Barium is not believed to be an essential human element,⁴ and both human and animal studies have shown that barium is a general muscle stimulant, partic-

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ularly to the heart muscle.⁶ Human symptoms following acute ingestion include salivation, vomiting, diarrhea, hypertension, twitching, and flaccid paralysis of the skeletal muscle. Severe poisoning leads to respiratory muscle paralysis and ventricular fibrillation that can result in death. The fatal dose of ingested barium chloride is reported to be 0.8-0.9 g (550-660 mg as barium).⁵

Barium is a bone-seeking element and possesses chemical and physiological properties that enable it to replace calcium. Barium replacement of calcium will affect the adrenal gland and the release of hormones by the gland.

Because of the lack of data on the effects of ingesting barium in drinking water, the MCL of 1 mg/L was originally established by the extrapolation of health data from industrial exposure, and on the assumption that 90 percent of the barium ingested is absorbed into the blood stream via the gastrointestinal tract.¹ Most recent animal studies show that absorption rates for barium decrease from 90 percent in young animals to less than 10 percent in adults.⁶ These data suggest, therefore, that very young children will absorb more barium than adults.

Until 1978-1979, no epidemiological studies had been completed to assess the chronic effects on humans ingesting barium in drinking water. To expand the knowledge of the health effects of barium ingestion, an EPA-sponsored study was conducted in northern Illinois to determine whether health effects could be identified in communities exposed to barium in their drinking water.⁷ The study revealed a higher death rate in communities exposed to barium at the 2-mg/L level as opposed to communities with no significant exposure to barium. The epidemiological data also showed significant differences in the blood pressure of the male population of communities having 7 mg/L in their drinking water, in comparison to communities with only 0.1 mg/L of barium. The investigators emphasized the need for caution in data interpretation because of the factors that could not be controlled in the study. Moreover, the study did not result in a definitive conclusion on a no-effect level of barium in drinking water that would permit the investigators to recommend a safe standard for barium.

Because of the higher death rate with barium concentrations greater than 2 mg/L and the elevation in blood pressure at 7 mg/L reported in this study, R.J. Garner, director of the Health Effects Research Laboratory (HERL), USEPA, advised that the current barium limit of 1 mg/L not be relaxed and that communities exceeding the MCL should proceed with plans to reduce barium exposure.⁷ Both the investigators and Garner agreed

that more data were needed to better identify a no-effect level of barium in drinking water.

Barium is not a serious problem in most drinking water supplies, although it is frequently detected in trace amounts in surface waters and drinking waters. Kropp and Kroner reported a barium detection rate of 99.4 percent of 1577 water samples from lakes and streams in the US collected from 1962 to 1967.⁸ The minimum, maximum, and mean concentrations were 0.002, 0.34, and 0.043 mg/L, respectively.

The 1969 USPHS community water supply survey showed only one finished water sample from 967 water supplies (less than 1 percent) that exceeded the 1-mg/L limit.⁹ Furthermore, the October 1973¹⁰ and April 1975¹¹ reports on the chemical analysis of the interstate carrier water supply systems reported no violations of the barium limit. Finally, a very recent EPA study designed to develop relationships between inorganics in tap water and cardiovascular mortality rates reported a high frequency of detection of barium, but in low concentrations.¹² For example, barium was detected in 94.3 percent of the 35 areas surveyed; the survey included the analysis of 3834 individual household water samples. Using mean barium values for the 35 areas, the maximum "mean" was 0.35 mg/L; the minimum "mean" was 0.009 mg/L; and the mean "mean" was 0.067 mg/L.

Although barium is not commonly found in groundwater, a few areas of the US do have very significant levels of barium in their source water, the most noteworthy being in northern Illinois. The barium concentration in the groundwater in this area has been reported to be as high as 19 mg/L, with 2-7 mg/L being a common range.¹³

Barium chemistry overview. Barium is one of the alkaline earth metals, and thus it has chemical and physical properties similar to calcium, radium, magnesium, and strontium, the other elements in this group. In chemical behavior barium is more similar to radium, also included in the EPA drinking water regulations, than to the other three elements.

Barium occurs in only one major form as a divalent cation, Ba^{++} . The sulfate and carbonate salts are relatively insoluble; barium sulfate is more insoluble than calcium sulfate. The solubility of barium sulfate is reported to be 2.2 mg/L in pure water at 25°C, and of barium carbonate to be 16 mg/L under the same conditions.¹⁴ Barium sulfate (barite) is a common mineral, and because of its low solubility, waters containing sulfate should not contain any significant amounts of dissolved barium. The low soluble level of barium sulfate also suggests that alum and ferric sulfate coagulation should be effective methods for

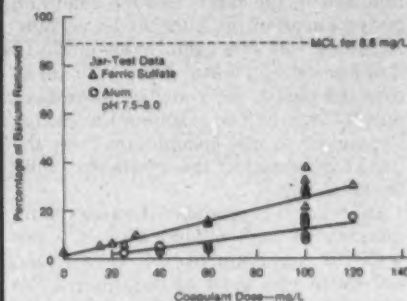


Fig. 1. Effect of Coagulant Dose on Barium Removal From Well Water by Coagulation Treatment

Barium Concentration—7.0-8.6 mg/L¹⁵

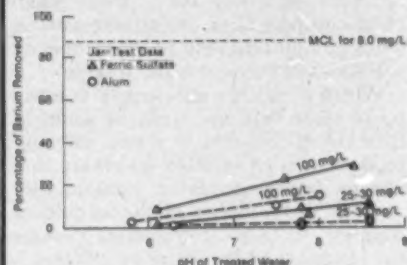


Fig. 2. Effect of pH on Barium Removal From Well Water by Coagulation Treatment

Barium Concentration—7.8-8.0 mg/L¹⁵

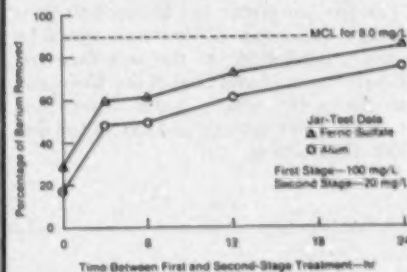


Fig. 3. Effect of Two-Stage Coagulation on Barium Removal From Well Water

Barium Concentration—7-8 mg/L¹⁵

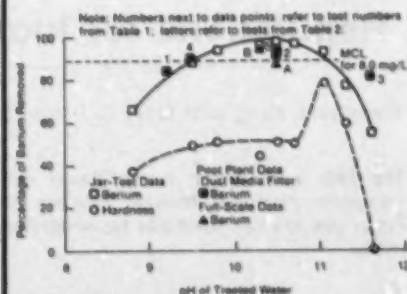


Fig. 4. Effect of pH on Barium Removal by Lime Softening

Barium Concentration—7.8 mg/L¹⁵

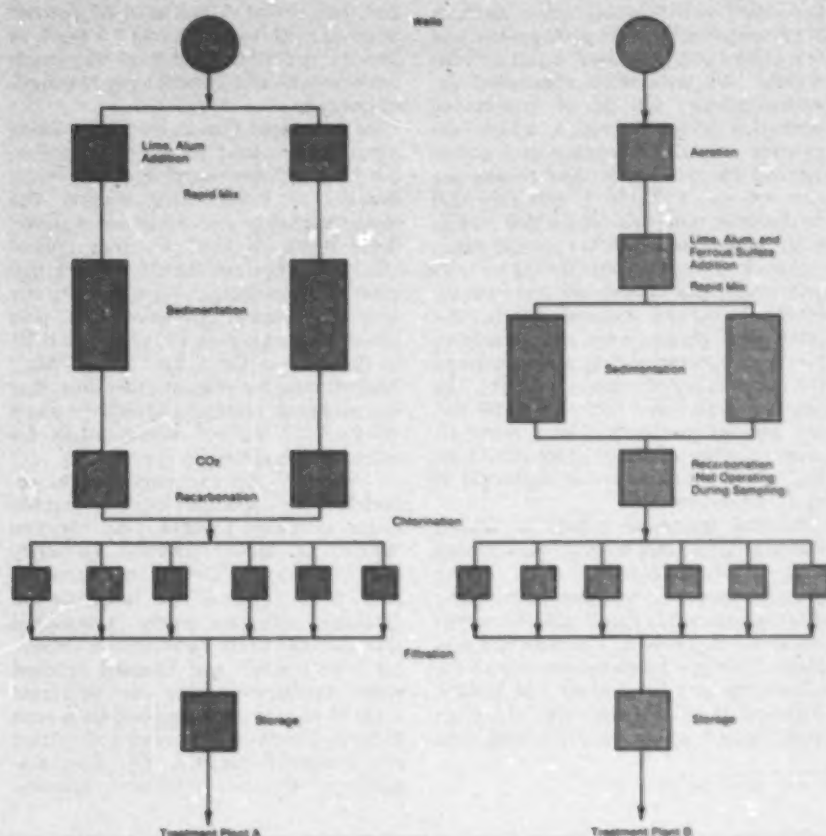


Fig. 5. Flow Diagram of Full-Scale Lime Softening Treatment Plants

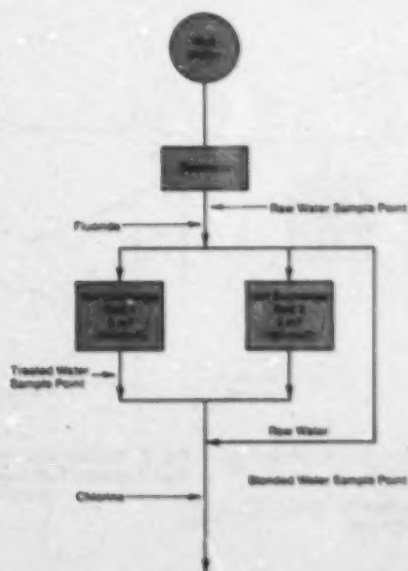


Fig. 6. Flow Diagram of Ion Exchange Softening Plant C
Constructed in 1964; Softening Cycle of 760 KL (200 000 gal)

barium removal, even though these are not good techniques for calcium removal. Pilot plant tests (discussed in the following section) indicate that the formation of barium sulfate may be a very slow process, however, and thus not a good mechanism for removal.

Many metals, such as cadmium, lead, and chromium, form insoluble hydroxide complexes and may be precipitated from solution by pH adjustment. The formation of barium hydroxide, $Ba(OH)_2$, is possible but the complex is very soluble (about twenty times more soluble than barium sulfate), and thus should not be a significant factor in removing barium by conventional coagulation treatment.¹⁴ The chloride form is even more soluble than the hydroxide form, and waters containing chloride result in a higher solubility of barium sulfate.¹⁴

Because barium has chemical properties similar to calcium and magnesium, treatment methods effective for the removal of these elements should also be effective for barium. This suggests, therefore, that lime softening and ion exchange methods used to remove hardness should be good techniques for barium removal. The capacity of ion exchange resins for barium removal should be dependent on the concentration of calcium and magnesium and the selectivity of one or both of these elements over barium.

Treatment methods. Because barium is not a frequent problem in drinking water, very few studies have been conducted on its removal. Laboratory and pilot plant studies for barium removal by conventional coagulation and lime softening methods have been conducted by the Drinking Water Research Division (DWRD) of the USEPA at the Environmental Research Center in Cincinnati. Except for these data (reported here), very limited or no data exist on barium removal by other treatment methods, such as ion exchange, activated carbon, reverse osmosis, and electrodialysis.

Conventional coagulation. Laboratory jar-test studies for barium removal by alum and ferric sulfate coagulation treatment have been conducted by Logsdon et al.¹⁵ These researchers expected to remove a very high percentage of the 7-8 mg/L of naturally occurring barium from an Illinois groundwater with both coagulants, by forming insoluble barium sulfate during the coagulation process. Their expectations were not achieved, however; removals did not exceed 30 percent even when the dose was as high as 120 mg/L (Fig. 1). Their data also revealed a small pH effect, with removals increasing slightly as the pH increased from about 6 to 8.5. Iron coagulation was slightly more effective than alum (Fig. 2).

The reason for the lack of high removals was suggested by the authors to be

supersaturation of barium and inadequate time for the barium sulfate precipitate to form. A second series of tests were therefore conducted in which two-stage coagulation was carried out. The first stage consisted of treatment with 100 mg/L of either alum or ferric sulfate and 1 hr of sedimentation. The settled water was withdrawn and kept in separate jars for second-stage treatment at intervals of 3, 6, 12, and 24 hr. Second-stage treatment consisted of dosing the settled waters with 20 mg/L of the same coagulant, 1 hr of sedimentation, and centrifugation to represent filtration.

The results of two-stage treatment showed higher total removals, up to about 80 percent (Fig. 3). These data suggest that supersaturated barium sulfate solutions form the crystalline phase slowly, and thus coagulation treatment for removal of large amounts of barium would be a very costly solution.

Lime softening. Jar-test data, pilot plant tests, and limited full-scale treatment plant information indicate that barium can be effectively removed from water by lime softening, and that the efficiency is pH dependent. Logsdon et al.¹³ conducted jar-test studies at pH 9 to 11.5 using Illinois groundwater having 7-8 mg/L of naturally occurring barium. The results of these tests, plotted in Fig. 4, show that barium removal is pH dependent. Removals increased from 65 percent at pH 8.7 to a peak of 96 percent at pH 10.5, and then declined to 55 percent at pH 11.6. In order to achieve the barium MCL, 87.5 percent removal was required; this was attained from about pH 9-11.

Because barium is chemically similar to calcium and magnesium (hardness), the hardness removal results are also shown in Fig. 4 for comparison. The barium and hardness removal curves have similar characteristics, except in the pH range of 10.6 to 11.4 when the hardness removal curve develops a sharp increase. The reason for this sharp increase is suggested to be the removal of magnesium. The raw water had a magnesium concentration of 21 mg/L, and magnesium will precipitate in the hydroxide form at pH 10.6 (excess lime softening). As the pH is increased by the addition of more lime, an excess of calcium occurs and the percentage of hardness removed decreases.

Logsdon et al.¹³ suggested that the removal mechanism for barium is the precipitation of insoluble barium carbonate, the same mechanism as for calcium. The decline in barium removal above pH 11 was thought to be caused by the formation of the more soluble barium hydroxide. The formation of magnesium hydroxide at roughly the same pH level adds support to this suggestion.

To verify the jar-test results reported by Logsdon et al.,¹³ DWRD conducted five pilot plant lime softening tests using

water from the same area of northern Illinois. The test water was trucked from two separate locations to the DWRD laboratory in Cincinnati, where the tests were run using the pilot plant system and test procedures described in part 2 of this series.* All tests were conducted for approximately 100 hr of continuous operation except for test 5, which was run for only 77 hr because of a power failure. The pilot plant test results are summarized in Table 1, and the dual media filter removals are plotted on Fig. 4 for comparison with the jar-test data.

Although the test water for the jar tests and pilot plant studies did not contain identical barium concentrations, the pilot plant results were comparable to the jar-test removal data and confirmed the dependency of removals on pH. The best removals were achieved at pH 10.5 (93 and 94 percent); lower removals resulted at the lower pH of 9.2 and 9.5 (84 and 91 percent) and at the higher pH of 11.6 (85 percent).

Several treatment plants in Illinois soften groundwater that contains natural barium. DWRD collected three sets of samples from two of these plants (flow diagrams shown in Fig. 5), and the results are given in Table 2. The data are also plotted in Fig. 4 for comparison with the laboratory and pilot plant test results. Although the plants were very old, operated beyond design capacity, and were

undergoing changes in operation, the barium removal results were comparable to the DWRD laboratory and pilot plant test data. Plant A achieved 88 percent removal with water having 7.5 mg/L of barium, and plant B achieved 95 percent removal with water containing 17.5 mg/L of barium.

Ion exchange. Cation exchange, using natural greensand or synthetic resins, has been utilized successfully for many decades to soften hard waters. The cation exchange selectivity series shows these resins to have an even greater affinity for barium than for either calcium or magnesium. A typical selectivity series for divalent cations of strong-acid cation exchange resins is reported as $Ba > Pb > Sr > Ca > Zn > Fe > Mg$.¹⁴ This information suggests, therefore, that ion exchange softening should be more efficient for barium removal than for calcium or magnesium removal.

Laboratory ion exchange studies reported in the literature¹⁵ confirm that the cation exchange process is an effective method for barium removal. To verify this information, DWRD conducted a short field study on two full-scale ion exchange softening plants in northern Illinois. This study consisted of collecting raw, treated, and blended finished water samples through one treatment cycle of one ion exchange bed from each plant to determine the amount of barium and hardness removed. The flow diagrams of the two treatment systems,

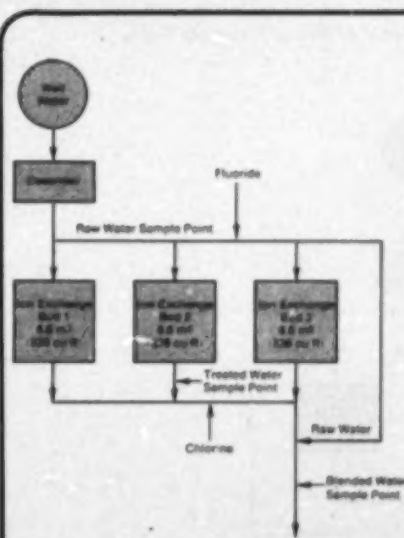


Fig. 7. Flow Diagram of Ion Exchange Softening Plant D
Constructed in 1964; Softening Cycle of 1.3 ML (350 000 gal)

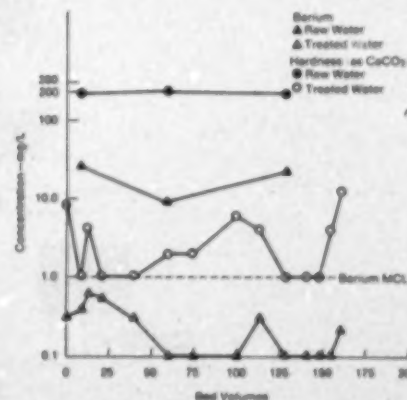


Fig. 8. Barium and Hardness Removal From Well Water by Full-Scale Ion Exchange Treatment Plant C

*Jour. AWWA, 70:7378 (Jul. 1978).

labeled plants C and D, are shown in Fig. 6 and 7, respectively.

Treatment plant C had two ion exchange beds and was treating raw water having a barium concentration of about 10 mg/L and a hardness of 218 mg/L (as CaCO_3). The second plant, D, consisted of three ion exchange beds and was treating well water having a barium level of 19 mg/L and a hardness of 230 mg/L (as CaCO_3).

The barium and hardness removal data collected from ion exchange bed 1 of treatment plant C are plotted in Fig. 8. These data show that the barium was reduced to less than 1 mg/L through 153 bed volumes [714 000 L (188 000 gal)]. This system was operated on a flow basis rather than on a hardness breakthrough basis, and thus the treatment cycle was terminated before either hardness or barium broke through the ion exchange bed. The percentage removals ranged from 94 to more than 99 percent for barium, and from 95 to more than 99 percent for hardness (Fig. 8). Eight finished water samples (blended water) showed barium to range from 2.4 to 4.5 mg/L.

The test data of one treatment cycle of ion exchange bed 2 of plant D are plotted in Fig. 9. This treatment cycle was run past both barium and hardness breakthrough; the barium concentration of the treated water was 5.8 mg/L, and the hardness concentration 142 mg/L (as CaCO_3) at shutdown. Barium breakthrough (1 mg/L) occurred around 100

bed volumes [787 kL (207 000 gal)]. The raw water for plant D had a barium concentration of 19 mg/L, almost twice the level in the raw water of plant C (10 mg/L). Therefore, barium breakthrough was expected to occur earlier. The data also show that hardness broke through (85 bed volumes) before barium.

On a percentage removal basis barium removal exceeded hardness removal very significantly, as shown in Fig. 10. At shutdown, 70 percent of the barium was being removed as compared to only 38 percent of the hardness.

Blending of raw water with treated water to increase the hardness, and thus stabilize the distribution water, was practiced at both plants. Five blended water samples collected from plant D during the test run had a barium concentration range of 1.5–4.0 mg/L. These data indicate that blending may not always be feasible for barium treatment. If the raw water has a high barium concentration, as experienced at both of these test locations, even a small amount of blending will raise the barium level above the MCL. If blending is not possible, restabilization of the very soft water will be necessary. Restabilization can be accomplished by several methods, such as blending the treated water with a barium-free water or adding lime.

To evaluate the potential disposal problem of the high barium wastewater, twelve water samples were collected during the regeneration cycle of plant D.

A plot of the barium concentration with time is given in Fig. 11; the peak concentration was slightly above 6000 mg/L. The calculated amount of barium in the brine waste was about 18 000 g, or 85 percent of the amount calculated to be removed (22 100 g) during the treatment cycle. The average calculated barium concentration of the 35 kL (9300 gal) of wastewater was 534 mg/L.

Activated carbon. Because calcium and magnesium are not absorbed by either powdered activated carbon (PAC) or granular activated carbon (GAC), the potential for barium removal by PAC or GAC has always been assumed to be low. Data from a PAC study by Thiem and O'Connor¹² and from the DWRD pilot plant studies confirm this conclusion. Thiem and O'Connor reported on the effectiveness of three different materials, PAC 1,* PAC 2,† and PAC 3‡ on the removal of 5 mg/L of barium at pH 7, 8, and 9. The effect of PAC doses up to 100 mg/L was also studied. The results of the laboratory tests showed that the highest removal achieved was only 7 percent with a 100-mg/L dose of PAC 1. Although the optimum pH for two of PAC materials was slightly different, the ranking of the three materials for barium removal at the three pH values remained the same: PAC 1, PAC 2, PAC 3. The optimum pH for PAC 1 was pH 9, and for PAC 2, pH 7.

*Amoco PA-121, Amoco Research Corp., Chicago, Ill.
†Dacron HDB, KCI Americas, Inc., Wilmington, Del.
‡Duckett Aqua, Wastwater Corp., Covington, Va.

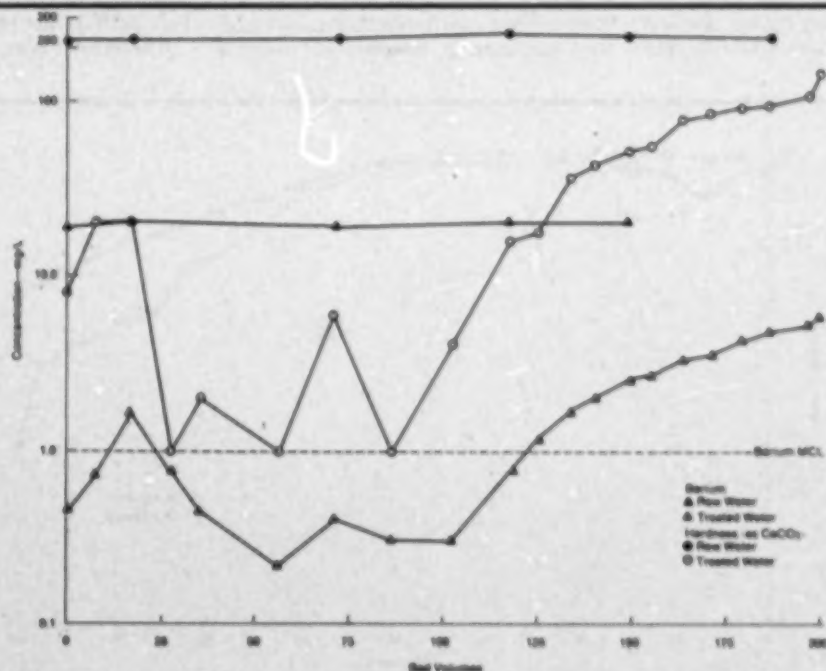


Fig. 9. Barium and Hardness Removal From Well Water by Ion Exchange Treatment Plant D

No change in removal was noted with pH for PAC 3; removals were 1 percent or less under all conditions.

The lime softening pilot plant data of Table 1 show no difference in removals between the dual media and GAC filters. These data indicate that the removal mechanism in the GAC filters is only filtration; no additional barium is being removed by GAC adsorption.

Reverse osmosis and electrodialysis. Reverse osmosis (RO) and electrodialysis (ED) are very effective treatment processes for hardness removal, and thus they should also be very efficient for barium removal. RO laboratory studies have been conducted for barium removal by Mixon¹⁸ and by DWRD, and the test results support this conclusion. Mixon achieved 98-99 percent removal of 9.13 mg/L of barium in tap water by three different cellulose acetate (AC) membranes. A high removal of 98.6 percent was also achieved with tap water containing 7 mg/L of barium in combination with five other metal ions.

DWRD conducted two short RO laboratory experiments for the removal of naturally occurring barium (7 mg/L) in a northern Illinois groundwater. The tests consisted of treating 236-L and 200-L batches of water with a small RO system (AC membrane) operated at 1140 and 1240 kPa (165 and 180 psi), respectively. The test results were comparable to those achieved by Mixon; barium removal was 95-99 percent at 1140 kPa (165 psi) and 95-98 percent at 1240 kPa (180 psi).

A general literature review did not reveal any specific data on the removal of barium from drinking water by ED.

Because of the similarities in treatment capabilities, however, this technique should be as effective as RO.

Barium treatment summary. Conventional coagulation treatment is not an effective method for barium removal, even when high doses of sulfate coagulants are used. Test data suggest that two-stage coagulation is required to achieve a barium removal of about 70 percent. This is expensive and thus impractical.

The two softening methods, ion exchange and lime precipitation, are very good methods for barium removal. Full-scale treatment data show that both methods are capable of lowering barium concentrations as high as 17-19 mg/L to below the MCL of 1 mg/L. One shortcoming of the ion exchange process is that the normal practice of blending raw and softened treated water is not always feasible with water having a high barium concentration. Stabilization of the very soft, treated water normally would be required to prevent any corrosion problems from developing in the distribution system.

Barium removal by lime softening is pH dependent; the optimum range (93-95 percent) is pH 10-10.5. Below and above this range, removals decrease with decreasing and increasing pH, respectively.

Powdered and granular activated carbon are ineffective methods for barium treatment. Laboratory data show that PAC achieved less than 7 percent removal under optimum conditions, and GAC essentially no removal. RO and ED are good methods for hardness removal, and thus are equally effective for barium

removal (95-98 percent).

Because barium is not a widespread and frequent problem, and because several conventional water treatment methods (ion exchange and lime softening) are good methods for barium treatment, DWRD has no specific research projects devoted to barium treatment.

Radionuclide Removal From Water

Health effects. Radioactivity, either naturally occurring or man-made, has been known for many years to produce detrimental biological effects in man: developmental abnormalities, cancer, and death. The National Academy of Science reports that radiation may conceivably cause cancer of virtually any type or at any site given the appropriate conditions of irradiation and host susceptibility.¹⁹ The primary basis for the EPA radionuclide regulations²⁰ for drinking water is the carcinogenic potential of this material. The carcinogenic potential of radioactivity was also the primary reason for the establishment of the 1962 USPHS regulations for drinking water.¹

The radionuclide regulations are more complex than the MCL established for the other inorganic contaminants. The MCL for the combination of radium-226 and 228 was set at 5 picocuries per litre (pCi/L). This concentration is slightly above the 3 pCi/L standard established for radium-226 alone by the USPHS in 1962.² The USPHS Drinking Water Standards also had a 10-pCi/L standard for strontium-90, whereas EPA includes strontium in the general regulation on beta particle and photon radioactivity.

The second part of the EPA radionu-

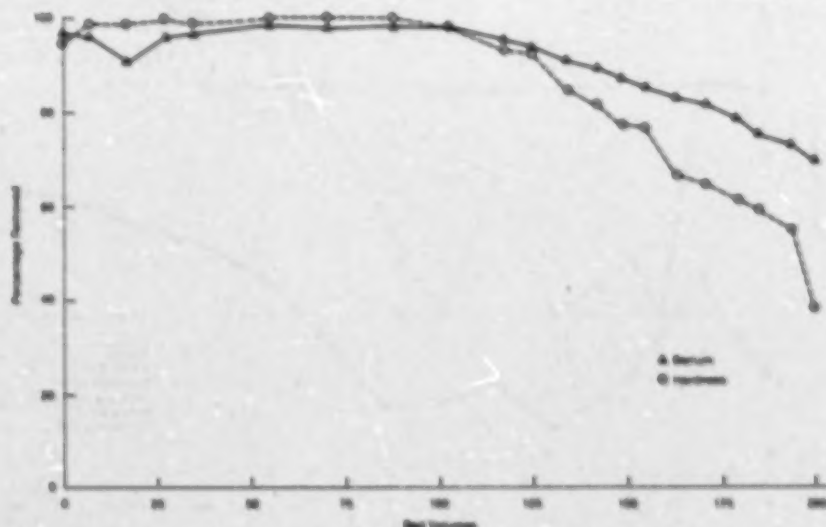


Fig. 18. Percentage of Barium and Hardness Removed From Well Water by Full-Scale Ion Exchange Treatment Plant D

slide regulations governs gross alpha activity, including radium-226 and 228. It states that the gross alpha activity shall not exceed 15 pCi/L. The third regulation that concerns man-made radionuclides states "the average annual concentration of beta particle and photon radioactivity from man-made radionuclides in drinking water shall not produce an annual dose equivalent to the total body or any internal organ greater than 4 millirem/year." The 1961 USPHS standards established gross beta concentrations of 1000 pCi/L as grounds for rejection of a water supply, except when more complete analysis indicated that concentrations of nuclides were not likely to cause exposure greater than the Radiation Protection Guides recommended by the Federal Radiation Council (FRC).¹⁶

A large body of information exists on the biological effects of radiation, and risk estimates for total body and specific body organ exposure have been published by a number of groups, including the National Academy of Sciences (NAS),¹⁷ the United Nations Scientific Committee on the Effects of Radiation (UNSCEAR),¹⁸ the International Commission on Radiological Protection (ICRP),¹⁹ and the National Council on Radiation Protection and Measurements (NCRP).²⁰ Most of the low dose-effect relationships have been derived from studies of high radiation doses, based on the assumption that the effects are linearly proportional to the dose. In establishing the MCL for radioactivity in drinking water, EPA considered many factors, including the source of radioactivity and all the estimated risk factors

for naturally occurring and man-made radionuclides.

Of the many radionuclides found in the environment, radium is considered the most significant because it is naturally occurring and frequently found in groundwaters in several sections of the US. Furthermore, radium is significant because it is similar to calcium in that it is a bone-seeking element; 80-85 percent of the radium retained in the body is deposited in bone.²¹

Bone cancer is not the only health risk from radium ingestion, but it is definitely the most significant factor. Using the risk estimates of the FRC and the NAS, a radium-226 concentration of 5 pCi/L in a drinking water system serving 1 million persons could result in an estimated health impact of 1.5 fatalities per year.²² Although 1989 data suggest that radium-226 is not as toxic as radium-228, more recent data indicate that the toxicities are about the same.²³⁻²⁴

The potential of other alpha particle radionuclides also exists in drinking waters. The MCL of 15 pCi/L was established on gross alpha particle activity, rather than on each individual radionuclide, because of the impracticality and the expense of monitoring. The MCL for gross alpha activity was based on the radioactivity of other alpha particle-emitting contaminants relative to radium. The 15 pCi/L gross alpha particle limit (which includes radium) is based on the conservative assumption that if the radium concentration is 5 pCi/L and the balance of the alpha particle activity is caused by the next most radiotoxic alpha particle-emitting chain, starting with lead-210, the total dose-to-bone relationship would be equivalent to less than 6 pCi/L of radium-226.

When establishing the regulations for radioactivity in drinking water, EPA also recognized the potential contamination of surface water supplies by man-made radionuclides that decay by beta and gamma emission. Because of the multitude of man-made radioisotopes and the impossible task of establishing an individual limit for each element, EPA established an MCL based on a total body dose of radiation from the ingestion of these radionuclides. Using risk estimates, the 4-millirem annual total body dose regulation suggests a fatal cancer risk of 0.4 to 2 cancer deaths per 1 million people per year.²⁵

Concentrations of most man-made radionuclides in drinking water causing 4-millirem/year exposure can be calculated using specific dose data from the National Bureau of Standards.²⁶ A list of these concentrations has been developed and published by EPA.²⁷ These data were calculated on the assumption that an individual consumes an average of 2 L of drinking water per day.

The most significant man-made radio-

nuclides are probably those resulting from atmospheric nuclear weapon testing, strontium-90 and tritium. The annual average concentrations yielding 4 millirem/year for a 2-L intake rate are 8 pCi/L for strontium-90 and 20,000 pCi/L for tritium.²⁸

Traces of radium have been found in many areas of the US. The results of radiological sampling from eight standard metropolitan statistical areas (SMSA) and the state of Vermont as part of the 1969 community water supply study showed radium-226 in 60 of 143 water samples analyzed.²⁹ However, only four of the 60 samples had radium-226 concentrations above the 5-pCi/L MCL (5.4, 5.4, 76.5, and 136 pCi/L). Although these data suggest that radium may not be a serious problem, other information indicates that radium will be a frequent problem in certain sections of the country, namely in northern Illinois, Iowa, central and western Florida, and in the uranium mining areas of the Rocky Mountain states.

In 1964 radium-226 was detected in 151 of 241 town water supplies studied in Iowa.³⁰ Nineteen of these supplies had concentrations at 5 pCi/L or above, and the maximum concentrations measured were between 15 and 20 pCi/L. Gilkeson³¹ studied the natural occurrence of radium in Illinois and found that high concentrations of radiation in drinking water were restricted to the Cambrian-Ordovician aquifer in northern Illinois. Water samples from numerous wells showed that more than 300 wells exceeded 3 pCi/L of gross alpha, some having up to 15 pCi/L of radium-226.

In Florida radium-226 is usually associated with phosphate deposits. Concentrations as high as 21 pCi/L have been measured in drinking water systems.^{32,33} Whether serious problems exist with other types of radionuclides in either ground or surface water is not known.

Radionuclide chemistry overview. Two of the three parts of the radioactivity regulations are general and therefore encompass at least 100 or more radioisotopes. Thus a discussion of the chemistry and treatment technology of radionuclides will be limited to radium, the radionuclide expected to be the most frequently occurring in drinking water.

Radium is an alkaline earth metal and thus it has chemical and physical properties similar to the other elements in this group—calcium, magnesium, barium, and strontium. Radium-226, an alpha emitter, is a member of the uranium series and has a half life of 1622 years. Radium-228, a beta particle emitter, is a member of the thorium series and has a half life of 5.75 years. Because the uranium series has been encountered more frequently in natural waters than the thorium series, radium-226 should be more commonly found in drinking water

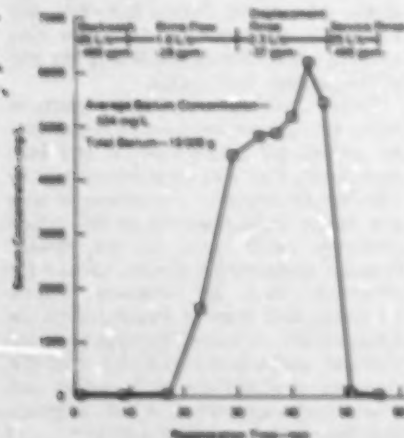


Fig. 11. Barium Concentration of Waste Water During Regeneration Cycle of Treatment Plant 0

and thus have the most significance to the water utility industry.

Radium is a cation, Ra^{++} , and was the last of the elements of the alkaline earth group to be discovered (in 1896). Comparatively little information exists on the chemistry of radium and radium compounds because of the newness, scarcity, and lack of interest in this element. Of the five alkaline earth elements, barium and radium are more similar to each other than to any other elements.

Chemistry handbooks^{22,23} report few data on the solubility of radium compounds. In some cases the data are even conflicting, particularly on radium sulfate. The solubility of radium sulfate is reported to be 2.1 mg/L and 0.021 mg/L, a hundredfold difference. The sulfate complex is the most significant, because its low solubility is the basis for the extraction of radium from mining ore. Other general information suggests that radium carbonate and chloride are less soluble than the barium salts. Radium solubility may have little significance in precipitation treatment because the MCL of 5 pCi/L is equivalent to 5×10^{-2} mg/L, a concentration many magnitudes below any of the reported solubilities of radium or barium compounds. Some radium chemistry information indicates, however, that radium solubility is significantly lower when it is found in combination with barium; the solubility is related to the total of the two elements in solution. Coprecipitation of radium with barium or other elements in the alkaline earth group may also occur. Because of the lack of information on radium chemistry, the predictive behavior of radium is based on the behavior of barium.

Treatment methods. Information on treatment will be confined primarily to radium, because it is beyond the scope of this report to present removal data on all the potential radionuclides included in the drinking water regulation. Furthermore, specific information on the effectiveness of water treatment processes for the removal of a wide variety of radionuclides has been reported by Straub.²⁴

Extensive treatment information for radium removal by softening techniques has been developed from several field studies in Iowa and Illinois.^{25,26} Information also exists on the use of reverse osmosis.^{27,28} Some data are available on conventional coagulation, but this method is considered ineffective and thus is not significant for radium treatment.

Conventional coagulation. The effectiveness of conventional coagulation treatment for calcium, magnesium, and barium suggests that this method should not be a good method for radium removal. A general literature review revealed no specific treatment studies on radium removal by conventional coagulation treatment using either alum or iron coagulants. Tsivoglou et al.²⁹ reported that

eight weeks of composite water samples from two full-scale conventional coagulation treatment plants in New Mexico showed radium (2-4 mg/L) to pass unchanged through the treatment plant, and thus not be removed by this process. Singley³⁰ suggests that chemical coagulation may remove up to about 25 percent of radium, but the results are variable and difficult to control.

Straub²⁴ reported that laboratory studies on the removal of strontium, another radionuclide and element of the alkaline earth group, have shown that conventional coagulation using either alum, ferric chloride, or ferric sulfate is not effective (0-15 percent) for this element of the group.³¹ This same author also states that conventional coagulation with sedimentation and filtration removes 96-98 percent of phosphorus-32 and less than 1 percent of iodine-131.³²

Because of the lack of success for the removal of all alkaline earth metals by coagulation treatment, DWRD did not conduct any laboratory studies by this method, but concentrated its efforts on studying the more promising methods of ion exchange and lime softening.

Lime softening. DWRD conducted two pilot plant tests for the removal of naturally occurring radium-226 from Illinois groundwater by lime softening at pH 9.8 and 10.6. These studies were conducted with the 0.1-L/s (2-gpm) conventionally designed pilot plant system and procedures described in part 2. The tests were run with the same waters and at the same time as the barium studies because the natural groundwaters used for testing contained both contaminants.

A summary of the two pilot plant tests is given in Table 3. Because of the complicated nature and the expense of the radium analysis, only three sets of samples were collected during the first test run and only two during the second run. The specific results have also been reported by Brinck et al.³³ The test data indicate that radium removal is pH dependent as was found with barium removal; at pH 10.6 dual media filter removals averaged 94 percent, decreasing to 84 percent at pH 9.50.

Radium removal information at full-scale lime soda ash softening plants in Iowa and Illinois was collected and reported by Brinck et al.³³ Radium reduction varied from 75 to 96 percent for waters having radium-226 concentrations of 5.8-9.3 pCi/L. Two Iowa systems reported pH measurements. A plant operated at pH 11.0 achieved a removal of 96 percent, while a plant operated at pH 10.1 removed only 75 percent.

Pilot plant and full-scale plant data suggest removals of 75-96 percent of radium-226, depending on the pH. At 75 percent the MCL of 5 pCi/L can be achieved by the process, providing the raw water concentration does not exceed

20 pCi/L. If 96 percent removal is attainable, the MCL can be met with a raw water concentration ≤ 125 pCi/L.

Lime and lime-soda ash softening studies have been reported on the removal of strontium.³⁴ The removals followed a pattern similar to calcium, barium, and radium removal, increasing with increasing chemical dosages of lime and soda ash from 67 to 99 percent. As for barium and radium removal, the removal mechanism suggested was coprecipitation with calcium.

Lime-soda ash softening is also reported to provide a 90 percent or better removal of barium-lanthanum-140, cadmium-115, scandium-46, yttrium-91, and zirconium-neobium-95.³⁵ The process is reported to be ineffective for tungsten-185 and iodine-131.³⁶

Ion exchange. Cation exchange is a very good method of removing radium and strontium from drinking water. Full-scale ion exchange softening plants in Illinois and Iowa achieved average removals of 81-87 percent of radium-226 from water having initial concentrations of 3.25-43 pCi/L.³⁷ A zeolite softening plant achieved an average reduction of radium-226 from 43 to 1.9 pCi/L (96 percent). Another plant was capable of lowering the radium-226 level from 5.7 to 0.2 pCi/L. In contrast to the problem with barium treatment of not being able to blend treated and raw water, many of the plants were able to blend raw with treated water and to meet the radium MCL in the finished water. The study results also indicated that radium-226 was continuing to be removed for a short time after hardness breakthrough.

Samples of regeneration wastes, softener brine, and rinse waters were measured and found to have concentrations of 320-3500 pCi/L. Additionally, the major portion of the radium-226 was found to be removed from the ion exchange beds during the first 10-30 min of the regeneration cycles.

Cation exchange has been shown to remove 95 percent or more of strontium-90, cesium-137, cadmium-115, and barium-lanthanum-140, elements present in solution as cations.³⁸ Strontium-90 was also found to be removed by the cation exchange resin after calcium breakthrough, suggesting a greater affinity for strontium than for calcium. Anion exchange will achieve equal results on tungsten-185, an anion. Yttrium-91, scandium-46, and zirconium-neobium-95 are removed partially by both cation and anion exchange resins, which suggests that they are in a colloidal form.³⁹

Activated carbon. No specific information was found on radium removal by FAC. The lack of success of PAC for calcium and barium removal suggests, however, that PAC would not be a good removal method for radium. The same reasoning also holds for GAC treatment,

TABLE 1
Results of Lime Softening Pilot Plant Tests for Barium Removal From Well Water*

Test Number	Date Started	Length of Tests, hr	pH of Treated Water	Average Raw Water Concentration		Percentage Barium Removed				Percentage Hardness Removed	
				Barium, mg/L	Hardness (as CaCO ₃), mg/L	Settled Water		Filtered Water		Filtered Water	
						1st Stage	2nd Stage	Dist. Media	CAC2	Dist. Media	CAC2
1	7/16/75	100	8.2	15.0	210	70		90	90	90	90
2	7/15/75	100	10.5	10.1	210	60	60	90	90	70	90
3	7/20/75	100	11.0	10.4	200	60	60	90	90	70	90
4	8/6/75	100	8.5	6.5	200	80		90	90	97	97
5	8/10/75	77	10.5	6.5	200	90	90	90	90	90	90

*Slurry groundwater containing naturally occurring barium. Two water sources are shown used for tests 1, 2, 3, and a second source for tests 4 and 5.

**Second settling stage followed recarbonation which lowered pH to 8.0.

†Pittsburgh 200, Colgate Corp., Pittsburgh, Pa.

TABLE 2
Barium Removal From Well Water by Full-Scale Lime Softening Water Treatment Plants

Treatment Plant	Treatment pH	Water Sample	Barium Concentration—mg/L				Hardness Concentration (as CaCO ₃)—mg/L	
			Raw Water	Settled Water	Recarbonated Water	Filtered Water	Raw Water	Filtered Water
A	10.5	1	7.5	0.01	1.00	0.01	270	70
		2	7.5	0.00	1.10	1.00	260	60
		3	7.5	0.00	1.00	0.70		
		4	7.5	0.04	1.00	0.80	270	70
		Average concentration (average percent removed)		(99)		(99)		
B	10.5	1	17.0	1.00		0.90	260	70
		2	10.0	1.00		0.90	210	60
		3	17.0	1.00		0.90		
		4	17.0	1.00		0.90	260	70
		Average concentration (average percent removed)		(99.4)		(99.2)		

TABLE 3
Results of Lime Softening Pilot Plant Tests for Radium-226 Removed From Well Water*

Test Number	Date Started	Length of Tests, hr	pH of Treated Water	Average Raw Water Concentration		Percentage Barium Removed				Percentage Hardness Removed	
				Radium-226, pCi/L	Hardness (as CaCO ₃), mg/L	Settled Water		Filtered Water		Filtered Water	
						1st Stage	2nd Stage	Dist. Media	CAC2	Dist. Media	CAC2
18	6/6/75	100	8.5	0.50	100	70		90	90	97	97
19**	6/10/75	77	10.5	0.60	200	80	80	90	90	90	90

*Slurry groundwater containing naturally occurring radium-226.

**Second settling stage followed recarbonation that lowered pH to 8.0.

†Pittsburgh 200, Colgate Corp., Pittsburgh, Pa.

‡Samples collected only on 6/6, 6/9, and 6/10.

§Samples collected only on 6/10 and 6/11.

TABLE 4
Radium-226 Removed by Full-Scale Reverse Osmosis Plants*

System Capacity		Radium-226 Concentration—pCi/L		Percentage Removed
m ³ /d	gpd	Raw Water	Treated Water	
5700	1000	0.4	0.20	50
757	200	0.5	0.25	50
570	100	1.0	0.50	50
200	70	10.0	1.0	90
110	40	0.2	0.10	90
110	30	10.0	0.5	97
60	5	20.0	0.5	90
5.1	1.0	10.1	0.5	90
3	0.5	11.1	0.55	90

*Source: T. J. Song et al. and W. L. Brack et al.

and the DWRD pilot plant data in Table 3 support this conclusion. The percentage removals for the dual media filters and the GAC filters were essentially the same, indicating that adsorption of radium-226 by the GAC material did not occur. Because removals by the GAC and dual media filter columns were identical, the GAC removal mechanism is attributed entirely to filtration.

Reverse osmosis and electrodialysis. Full-scale RO treatment system data have been developed for the removal of radium-226. Strick et al.¹⁰ reported 96 percent removal of 14 pCi/L of radium-226 in Iowa. Sney et al.¹¹ studied the radium-226 removal by eight RO systems in Florida and reported removals of 67-98 percent of radium concentrations ranging from 1.2 to 20.5 pCi/L. A summary of these data are shown in Table 4.

A general literature review did not reveal any specific data on radium removal by ED, which should also achieve high removal because of its similarity in treatment capabilities to RO.

Both RO and ED are generally effective for the removal of most ionic species. Thus these two techniques should be good treatment methods for most radionuclides. Their most advantageous application is for the treatment of drinking water containing a mixture of radionuclides that would require the combination of several treatment methods to be effective.

Radionuclide treatment summary. The radionuclide that has the most significance in drinking water is radium because it is a naturally occurring element

frequently found in drinking water above the MCL. Radium has properties similar to calcium and barium, and thus the treatment methods effective for these two elements are the best methods for the removal of radium.

Conventional coagulation will remove only a small percentage (0-20) of radium from water. This treatment method is applied primarily to surface waters and would not normally be used for treating groundwaters containing radium.

The two most practical and economical treatment methods for radium are ion exchange and lime softening. Full-scale treatment plant information has been developed to show that ion exchange softening (cation exchange) can achieve removals in the 91-97 percent range. Treatment information also indicates that radium is more selective than calcium because calcium breakthrough occurs before radium breakthrough.

Lime and lime-soda ash softening have been demonstrated on a full-scale plant level to achieve 75-96 percent removal of radium. Pilot plant studies and full-scale plant data indicate removal efficiency to be pH dependent. For example, DWRD pilot plant studies showed 96 percent removal at pH 10.6 and 84 percent removal at pH 9.5. If 90 percent removal can be achieved by either softening method, the radium MCL of 5 pCi/L can be achieved with water containing 50 pCi/L or less of radium.

Activated carbon treatment, both PAC and GAC, is ineffective for radium removal. RO and ED are, however, good methods for radium; full-scale RO treat-

ment data show removals in the 90-95 percent range to be easily achievable.

DWRD has conducted and sponsored several studies for radium removal. Because these studies have shown that ion exchange and lime softening are efficient methods for radium, no further research is now planned.

Treatment data exist to show that cation exchange resins will remove many cation radionuclides and anion exchange resins will remove anion radionuclides. Mixed bed ion exchange resins, RO, and ED are generally good treatment methods for the removal of mixtures of radionuclides. Specific treatment information is generally lacking for most radionuclides, however. Because of the lack of treatment data on man-made radionuclides, DWRD is developing plans to investigate methods to remove radionuclides occurring most often in drinking water. These studies will begin during fiscal year 1991.

Treatment Summary for Inorganic Contaminants

This report is the last of a five-part series that has expanded upon the summary information presented in the EPA document, *Manual of Treatment Techniques for Meeting the Interim Primary Drinking Water Regulations*.¹² The series has consisted of part 1 on fluoride and nitrate (June AWWA, 70:210R), part 2 on arsenic and selenium (June AWWA, 70:379R), part 3 on cadmium, lead, and silver (June AWWA, 70:1268R), part 4 on chromium and mercury (June AWWA, 71:840R), and finally this last report, part

TABLE 3
Summary of Effectiveness of Water Treatment Processes for the Removal of Inorganic Contaminants*

Contaminant	Conventional Coagulation		Lime Softening	Ion Exchange		Activated Alumina	Activated Carbon		Reverse Osmosis	Electrodialysis
	Alum	Iron ^b		Cation	Anion		PAC	GAC		
Arsenic ^c + III	0	0	0 pH < 10.5 L-G pH > 10.5	0	L	0	0	0 (from short)	0-2	0-25
+ V	0 pH < 7.5 0 pH > 7.5	0	0 pH < 10 0 pH 10-10.5 0 pH > 10.5 0 pH 9.5-10.5	0	0	0	0	0 (from short)	0	0
Barium	0	0	0	0	0	0	0	0	0	0
Calcium	0 > pH 9.5 0-0 > pH 9.5	0 pH > 9 0-0 pH > 9	0	0	0	0	0	0	0	0
Chromium + III	0	0	0 pH < 10.5 0 pH > 10.5	0	0	0	0	0	0	0
+ VI	0	0	0	0	0	0	0	0	0	0
Fluoride	0	0	0	0	L	0	0	0 (from short)	0	0
Lead	0	0	0	0	0	0	0	0	0	0
Mercury	0	0	0	0	0	0	0	0	0	0
Organic	0-20%	0-20%	0	0	0	0	0-2	0	0-25	0-50
Inorganic	0-20%	0-20%	0	0	0	0	0-2	0-2	0-2	0-50
Nitrate	0	0	0	0	0	0	0	0	0	0
Selenium + IV	0	0	0 pH < 7.5 L-G pH > 7.5	0	0	0-2	0	0	0	0
+ VI	0	0	0	0	0	0-2	0	0	0	0
Silver	0 pH < 9	0	0	0	0	0	0	0	0	0
Sulfate	0	0	0 pH 9.5-10.5	0	0	0	0	0	0	0

*0=ineffective, 0-20 percent 0-good, 70-90 percent 0-fair, 90-95 percent 0-excellent

^bResults based upon ferric iron complexing except as noted

^cRemoval of As III to As V will result in As III removals similar to As V.

^dEstimated

^eResults under controlled conditions, but not practical in water treatment

^fEfficiency dependent on toxicity

5 on barium and radionuclides. The information presented indicates that no one treatment technology is ideal for all contaminants, although reverse osmosis and electrodialysis are generally effective for all contaminants. These two treatment methods are applied principal-

ly for desalting seawater and brackish groundwaters that are low in turbidity. They cannot be utilized on turbid surface water without extensive pretreatment, and thus would not be practical for removing contaminants from surface waters.

TABLE 6
Most Effective Treatment Methods for Removal of Inorganic Contaminants

Contaminant	Most Effective Treatment Methods
Arsenic	As V—iron coagulation, pH 6-8; alum coagulation, pH 6-7; excess lime softening; activated alumina, pH 5-6
Barium	As III—oxidation treatment of As III to As V; use same treatment list for As V
Cadmium	lime softening, pH-11; ion exchange softening
Chromium	iron coagulation, above pH 8; lime softening; excess lime softening
Fluoride	Cr III—iron coagulation, pH 6-8; alum coagulation, pH 7-8; excess lime softening
Lead	Cr—ferrous sulfate coagulation, pH 7-8.5
Mercury	ion exchange with activated alumina or bone char
Nitrate	iron coagulation, pH 6-6; alum coagulation, pH 6-9; lime or excess lime softening
Radium	inorganic—ferric sulfate coagulation, pH 7-8; granular activated carbon
Selenium	organic—granular activated carbon
Silver	ion exchange with anion resin
	lime softening; ion exchange with cation resin
	Se IV—ferric sulfate coagulation, pH 6-7; ion exchange with anion resin or activated alumina; reverse osmosis
	Se VI—ion exchange with anion resin or activated alumina; reverse osmosis
	ferric sulfate coagulation, pH 7-8; alum coagulation, pH 6-8; lime or excess lime softening

TABLE 7
Most Probable Applications of Water Treatment Processes for Inorganic Contaminant Removal

Treatment Process	Principal Application for Water Treatment	Inorganic Contaminant Treatment Capability Effectiveness*			Most Probable Application for Inorganic Removal
		High	Moderate	Low	
Convention coagulation	Clarification of surface waters	Cd Cr III Cr VI As V Ag Pb	As III Se IV Hg(O) Hg(I)	Ba F NO ₃ Ra Se VI	removal of Cd, Cr, As, Ag, or Pb from surface waters
Lime softening	removal of hardness from ground and surface water	Ba Ra Cd Cr III As V Pb	Se IV As III Hg(I) F	Cr VI NO ₃ Se VI Hg(O)	removal of Ba or Ra from groundwaters; removal of Cd, Cr III, F, As V, or Pb from hard surface waters requiring softening
Cation exchange	removal of hardness from groundwaters	Ba Ra Cd Pb Cr III		As Se NO ₃ F Cr VI	removal of Ba or Ra from groundwaters
Anion exchange	removal of nitrate from groundwaters	NO ₃ Cr VI Se	Ba Ra Cd Pb Cr III		removal of NO ₃ from groundwaters
Activated alumina	removal of fluoride from groundwaters	F As Se		Ba Ra Cd	removal of F, As, or Se from groundwaters
Powdered activated carbon	removal of taste and odors from surface waters		Hg(I) Hg(O) Cd	Ba Ra Cr III F NO ₃ Ag	removal of Hg from surface waters during emergency spills
Granular activated carbon	removal of taste, odors, and organics	Hg(I) Hg(O)	Cd	Ba Ra Cr III F NO ₃	removal of Hg from surface or groundwaters
Reverse osmosis and electrodialysis	desalting of sea water or brackish groundwaters	As V Ba Cr Pb Cd Se Ag F Ra Hg	NO ₃ As III		removal of all inorganics from groundwaters

*High—greater than 80 percent; moderate—20 to 80 percent; low—less than 20 percent

The effectiveness of conventional water treatment processes, coagulation and filtration, lime softening, and ion exchange softening, varies in capability to remove the inorganic contaminants. These processes are very effective for some contaminants, and moderately or completely ineffective for others. The degree of treatment capability is generally dependent on several factors: contaminant form, valence, and concentration; pH of the treatment process; type (surface or ground) and quality (turbidity, TDS, and so forth) of water; type and amount of coagulant or other chemical additive; and the filtration, adsorption, or ion exchange media. Thus exact removal percentages cannot be assigned to a treatment process for any specific contaminant. However, the laboratory, pilot plant, and full-scale plant data and information presented in this series do provide a guide for selecting the best treatment method and operating condition, and for determining probable removal ranges for each contaminant. The treatment information has been summarized in matrix form for all contaminants and treatment processes in Table 5. In some cases when information was not available or was inadequate, removal estimates were developed by the authors using their best judgment. The matrix of Table 5 indicates that different methods are the most effective for the removal of each contaminant. For clarity, the most effective methods for the control of inorganic contaminants are summarized in Table 6.

Although a treatment process may be good for removing a contaminant, it may not be a practical or economical method. For example, neither ion exchange, reverse osmosis, nor electrodialysis are practical methods for treating surface waters and thus would not be used to remove a surface water contaminant even though the method may be effective. Consequently, certain treatment processes are considered to be more practical than others although both may be equally effective. Table 7 summarizes the treatment information according to treatment processes and the most practical or probable application. This table is also useful for evaluating the capability of an existing plant to solve a potential problem.

The major considerations, if not the most significant factors, in the selection of a treatment method are the economics—capital and operating costs. If modifications to or changes in the operation of an existing plant can solve the problem, only a slight increase in operating cost may occur, or possibly no cost increase at all. On the other hand, if no facility exists the costs will be the expense of constructing and operating a new treatment plant.

Because of the interest in the costs of

water treatment processes for the removal of the contaminants included in the NIPDWR, EPA contracted with Culp/Wesner/Culp, Consulting Engineers, Inc., for a detailed study of the construction and operation and maintenance costs for unit water treatment processes. The study was completed in 1979; four detailed reports were published by EPA in August 1979.¹⁰⁻¹³ Construction and operation and maintenance cost curves were developed for approximately 100 unit processes; for each unit process, conceptual designs were formulated. All cost data are presented in January 1978 dollars, but a discussion on methods of cost updating is included.

The four reports show that the cost of treatment of the various unit processes is dependent on the design and size of the facility. A summary of the cost data is beyond the scope of this report, but copies of these detailed reports can be obtained from the Drinking Water Research Div., USEPA, Cincinnati, Ohio.

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